TUNABLE ELECTROOPTIC ADD-DROP FILTER
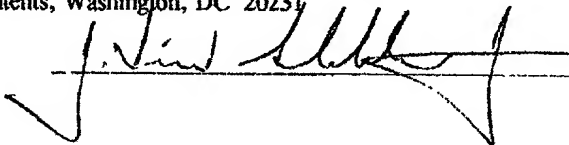# APPARATUS AND METHOD

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1 **Tunable Electrooptic Add-Drop Filter Apparatus and Method**
2
3

4 **Related Applications**

5 The applicants claim the benefit of the provisional patent application filed on January 17,

6 2001, application serial number 60/262,356.

7

8 **Field of the Invention**

9 This invention relates to a tunable electrooptic add-drop filter apparatus and method. In

10 particular, the invention relates to a tunable electrooptic add-drop filter apparatus and method in

11 filters fabricated on a birefringent electrooptic substrate whereby a narrow range of optical

12 frequencies are added to an optical fiber and a narrow range of optical frequencies are dropped

13 from a fiber while leaving other frequencies unaffected.

14

15 **Background of the Invention**

16 Wavelength division multiplexing is widely used in fiber optic communication to

17 increase the data capacity of an optical fiber. Currently, 16, 32, or more data channels are

18 transmitted in parallel on a single mode fiber using different optical carrier frequencies for each

19 channel. To combine and separate these channels, a variety of frequency-selective components

20 have been developed, including multilayer dielectric coatings, fiber Bragg gratings, arrayed

21 waveguide gratings, and Mach-Zehnder chains. None of these techniques satisfies industry

22 requirements for high-speed tunability and wide frequency tuning range.

1   An example of a prior-art electrooptic tunable filter (EOTF) for performing the add-drop

2   function is illustrated in Fig. 1. Such a filter has been demonstrated previously by applicants at

3   Texas A&M University in the substrate material lithium tantalate (LiTaO$_3$) [1].

4   The substrate for the prior art tunable filter (Fig. 1) is a single-crystal of a birefringent

5   electrooptic material such as lithium niobate (LiNbO$_3$) or lithium tantalate (LiTaO$_3$). The

6   waveguides are single mode for both TE and TM polarizations. Between the two directional

7   coupler polarizing beam splitters (PBS's) is a spatially periodic dielectric film to produce

8   polarization conversion, and electrodes for applying a tuning voltage.

9   Wavelength selectivity is determined by the phase-matching condition which governs

10   coupling between the polarization states induced by the periodic film, as described by

$$\Delta = \frac{2\pi\nu(n_1 - n_3)}{c} \pm \frac{2\pi}{\Lambda},\tag{1}$$

12   where Δ is the phase mismatch constant, ν is the optical frequency, n_1 and n_3 are the principal

13   refractive indices of the birefringent substrate material, and Λ is the spatial period of the film.

14   The frequency ν_j for which maximum polarization conversion occurs corresponds to the phase-

15   matching condition $\Delta = 0$. For frequencies far from ν_j, Δ is large and very little polarization

16   conversion will take place.

17   Tuning is accomplished in this prior art device by applying a voltage to electrodes on the

18   surface of the substrate. The resulting electric field in the waveguide region causes a change in

19   the birefringence ($n_1 - n_3$) via the linear electrooptic effect (Pockels effect). It follows from eq. 1

1   that a change in the birefringence causes a change in the frequency for which phase-matched

2   polarization coupling occurs.

3   Waveguides can be fabricated by a process which involves (1) deposition of a thin (90

4   nm) layer of titanium on the surface of the substrate, (2) patterning the titanium by a process of

5   photolithography and etching, and (3) diffusing the titanium into the substrate at 1050°C. To

6   produce the electrode pattern, a uniform aluminum film is deposited on the substrate, patterned

7   photolithographically, and etched. Finally, in the case of the tunable filter, a silicon dioxide film

8   is deposited at 350°C, masked with photoresist at room temperature, and etched to produce a

9   periodic bar pattern in the film. Strain resulting from the mismatch in thermal expansion

10   coefficients between film and substrate causes polarization conversion in the waveguides.

11   Another prior art design which is the subject of the co-pending patent application

12   09/737,206 is illustrated in Fig. 2. This design is promotes ease of manufacturing for the EOTF

13   by eliminating the need for PBS's, which are difficult to produce with the required tolerances.

14   The design of Fig. 2 differs from that of Fig. 1 at least in that the strain-inducing strips are offset

15   by $\Lambda/2$ in the top waveguide relative to the bottom one, and the optical path difference in the top

16   waveguide differs from that in the bottom one by $\lambda/2$.

17   An expanded view of a section of waveguide containing the strain pads and electrodes for

18   electrooptic tuning is shown in Fig. 3. The diagram in Fig. 3 could represent either the upper or

19   lower waveguide in the EOTF of either Fig. 1 or Fig. 2. The performance of the tunable prior art

20   filters of Fig. 1 or Fig. 2 is determined by the dependence of polarization conversion on optical

21   frequency in this waveguide section.

1   From eq. (1) it is determined that the spatial period Λ of the strain pads in the EOTF is

2   determined by the center frequency $\nu*$ of the spectral region in which the filter is intended to

3   operate and the refractive indices n_1 and n_3 of the birefringent substrate. The optical wavelength

4   region of most interest for optical fiber communication is 1530 -1560 nm. The frequency of the

5   center of this wavelength regime is $c/\lambda*$, with c the free-space speed of light and $\lambda* = 1545$ nm,

6   is $\nu* = 2.998 \times 10^8/1545 \times 10^{-9} = 1.929 \times 10^{14}$ Hz. For a lithium niobate substrate, with $n_1 =$

7   2.2118 and $n_3 = 2.1384$, it is calculated from eq. (1) that $\Lambda = 21.05$ μm.

8   A theoretical plot of the efficiency for polarization conversion X on optical frequency,

9   measured relative to the frequency for maximum polarization conversion, is given in Fig. 4. The

10   plot assumes that the substrate material is lithium niobate (LiNbO$_3$), a total length for the

11   polarization conversion region of 3.6 cm, and a uniform coupling constant induced by the strain

12   pads of 0.139 cm^{-1}. The same conditions apply to the plot of Fig. 5, in which the frequency scale

13   is expanded.

14   The length of the polarization conversion region was chosen to give the first nulls in the

15   conversion spectrum at $\pm$ 100 GHz relative to the central peak where the conversion efficiency is

16   a maximum. This would correspond to application in a wavelength-division-multiplexed

17   (WDM) communication system in which the channel spacing corresponds to the International

18   Telecommunication Union (ITU) specification of 100 GHz channel spacing. Thus, when a

19   particular channel is selected, the adjacent channel would correspond to a null, to reduce

20   crosstalk between channels.

1   The present invention addresses several deficiencies with the prior-art EOTF designs

2   described by the diagrams in Figs. 1-3 and the calculated response curves of Figs. 4 and 5.

3   Among these deficiencies are:

4   (1)   The required tuning voltage is too high. To tune the center frequency of one of

5   these prior art filters by 100 GHz is estimated to require about 7 V with an electrode spacing of

6   10 μm. Thus, tuning over 32 channels would require a voltage swing of 32 x 7 = 224 V, and to

7   tune over 64 channels. requires a voltage swing of 448 V. Such large voltages applied over such

8   a short distance causes degradation or even destruction of the EOTF.

9   (2)   The nulls in the conversion spectra of Figs. 4 and 5 are not equally spaced at the

10   desired 100 GHz separation. This adversely affects the need to minimize crosstalk in a WDM

11   system.

12   (3)   The time delay experienced by the light in traversing the EOTF is different for the

13   TE and TM polarizations due to the birefringence of the substrate. For example, for a substrate

14   length L_{sub} of 7 cm, with $n_1 - n_3 = .0734$, the delay difference is $L_{sub}(n_1 - n_3)/c$, with c the free-

15   space speed of light, which is calculated to be $7 \times 0.0734/2.998 \times 10^{10} = 17$ ps. Such a delay

16   leads to degradation of the "eye diagram" in a high-data-rate system, particularly at data rates of

17   10 Gb/s or higher.

18   (4)   The length of the polarization conversion region required to achieve a 50 GHz

19   channel spacing for WDM is not compatible with the size of available electrooptic substrates.

20   The length of the conversion region is inversely proportional to the channel spacing, so that for a

21   50 GHz spacing the conversion region needs to be $3.6 \times 2 = 7.2$ cm long. When the length

22   required for beam splitters and separating waveguide regions are taken into account, a 50 GHz

5

1   device could not be accommodated on the largest commercial lithium niobate substrates, which

2   are 3" (7.5 cm) in diameter.

3

4   **Summary of the Invention**

5   Accordingly, the tunable electrooptic add-drop filter apparatus and method of the present

6   invention includes, in filters fabricated on a birefringent electrooptic substrate, two input single

7   mode waveguides. A first beam splitter is connected to the waveguides and a polarization

8   converter is connected to each of the waveguides after the first beam splitters wherein each

9   polarization converter includes more than one set of spaced apart, spatially periodic, strain-

10   inducing pads. Electrodes are located in proximity to each of the polarization converters. A

11   second beam splitter is connected to the waveguides after the polarization converter and two

12   output single mode waveguides are connected to the second beam splitters.

13   In another aspect of the invention, the length of the polarization converter is given by the

14   formula: $L_{tot} = N_c L1 + (N_c-1)L2$ where: N_c = an integral number of polarization coupling

15   regions of length L1 and L2 = longer regions between the polarization coupling regions in which

16   polarization coupling does not occur. In a further aspect, a multiplicity of individual strain-

17   inducing pads are provided wherein the spacing between any two such strain-inducing pads is

18   equal to an integer times a particular minimum spacing between adjacent strain-inducing pads.

19   In another aspect of the invention, the widths of the strain-inducing pads are varied. In a further

20   aspect of the invention, the polarization converter has a center and edges and the width of the

21   strain-inducing pads is greater at the center of the polarization converter and tapers

22   monotonically towards the edges.

1   In another aspect of the invention, polarization maintaining fibers are connected to each

2   input and output single mode waveguide of the tunable electrooptic add-drop filter apparatus so

3   as to compensate for the difference in time delay for the two polarizations of light propagating in

4   and through the single mode optical waveguides in the birefringent electrooptic substrate. In a

5   further aspect of the invention, multiple tunable electrooptic add-drop filters of the present

6   invention are connected in series. In another aspect of the invention, the multiple electrooptic

7   add-drop filters have different values of Nc where Nc is an integral number of polarization

8   coupling regions.

9   In another embodiment of the invention, in filters fabricated on a birefringent electrooptic

10   substrate, a tunable electrooptic add-drop filter apparatus includes two input/output single mode

11   waveguides. A beam splitter is connected to the waveguides. A polarization converter is

12   connected to each of the waveguides wherein the polarization converter includes more than one

13   set of spaced apart , spatially periodic, strain-inducing pads. Electrodes are provided on the

14   substrate in proximity to the polarization converter. Finally, a reflector is connected to the

15   waveguides after the polarization converter.

16   In a further aspect of the invention, the length of the polarization converter is given by:

17   Ltot = NcL1 + (Nc-1)L2 where: Nc = an integral number of polarization coupling regions of

18   length L1 and L2 = longer regions between the polarization coupling regions in which

19   polarization coupling does not occur. In a further aspect of the invention, a multiplicity of

20   individual strain-inducing pads are provided wherein the spacing between any two such strain-

21   inducing pads is equal to an integer times a particular minimum spacing between adjacent strain-

22   inducing pads. In a further aspect of the invention, widths of the strain-inducing pads are varied.

7

1   In yet another aspect of the invention, the polarization converter has a center and edges

2   and the width of the strain-inducing pads is greater at the center of the polarization converter and

3   tapers monotonically toward the edges. In another aspect, a voltage tuner is connected to the

4   electrode. In another aspect of the invention, polarization maintaining fibers are connected to

5   each input/output single mode waveguide. In another aspect, an optical circulator is connected to

6   each input/waveguide.

7   In another embodiment of the invention, in filters fabricated on a birefringent electrooptic

8   substrate, a tunable electrooptic add-drop filter method is provided beginning with the step of

9   providing two input single mode waveguides on the substrate. A first beam splitter is connected

10   to the waveguides. A polarization converter is connected to the waveguides after the first beam

11   splitter wherein the polarization converter is conformed to include more than one set of spaced

12   apart, spatially periodic, strain-inducing pads. An electrode is connected to the polarization

13   converter and a second beam splitter is connected to the waveguides after the polarization

14   converter. Next, two output single mode waveguides are connected to the second beam splitter.

15   Finally, a voltage tuner is connected to the electrode and voltage is applied to the electrode

16   through the voltage tuner.

17   In a further aspect of the invention the step of forming the length of the polarization

18   converter is provided in accordance with the formula: $Ltot = NcL1 + (Nc - 1)L2$ where: Nc = an

19   integral number of polarization coupling regions of length $L1$ and $L2$ = longer regions between

20   the polarization coupling regions in which polarization coupling does not occur.

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8

Description of the Drawings

1

2   Other objects, features, and advantages of the present invention will become more fully

3   apparent from the following detailed description of the preferred embodiment, the appended

4   claims and the accompanying drawings in which:

5   FIGURE 1 is a schematic of a PRIOR ART EOTF design;

6   FIGURE 2 is a schematic of a PRIOR ART EOTF designed with relaxed beam splitter

7   requirements;

8   FIGURE 3 is a schematic expanded view of the polarization conversion/electrooptic

9   region of a PRIOR ART EOTF;

10   FIGURE 4 is a schematic illustrating the predicted polarization conversion efficiency vs.

11   optical frequency for the waveguide section illustrated in Figure 3;

12   FIGURE 5 is a schematic illustrating the plot of Figure 4 with the frequency scale

13   expanded;

14   FIGURE 6 is a schematic illustrating the tunable electrooptic add-drop filter of the

15   present invention;

16   FIGURE 7 is a schematic illustrating the predicted polarization conversion efficiency vs.

17   optical frequency for the waveguide section in accordance with the invention of Figure 6, plotted

18   using the following parameters: Nc = 12. L1 = .03 cm, L2 = .31 cm, k = 1.39 cm-1, ko = 0.35

19   cm-1;

20   FIGURE 8 is a plot of Figure 7 with expanded frequency axis;

21   FIGURE 9 illustrates an arrangement of three EOTFs of the present invention in series so

22   as to select one of Nc1 x Nc2 equally spaced frequency channels;

9

1   FIGURE 10 is a schematic illustrating frequency selection by EOTF's of the present

2   invention in series, with Nc1 = 4 and Nc2 = 3;

3   FIGURE 11 is a schematic illustrating reflective configuration for the EOTF of the

4   present invention;

5   FIGURE 12 is a schematic illustrating a four-port add-drop filter utilizing the reflective

6   EOTF of the present invention as illustrated in Figure 11;

7   FIGURE 13 is a another schematic illustrating the EOTF of the present invention as

8   illustrated in Figure 6, including an input and an output waveguide;

9   FIGURE 14 is a another embodiment of the present invention with slanted strain pads;

10   FIGURE 15 is a schematic of the present invention illustrating apodization of

11   polarization coupling strength by varying the width of the strain-inducing pads such that the

12   polarization coupling is strongest at the center of the polarization conversion region where the

13   pads are wider and weaker at the edges were the pads are narrower;

14   FIGURE 16 is an illustration of the present invention utilizing polarization maintaining

15   fibers to equalize the time delay for different polarizations of light; and

16   FIGURE 17 is an illustration of the polarization maintaining fibers connected to

17   conventional "non-polarization maintaining" single mode fibers.

18

19   **Detailed Description of the Invention**

20   The preferred embodiment of the present invention is illustrated by way of example in

21   Figures 6 - 17. To begin with, the tunable electrooptic add-drop filter 10 of the present invention

22   includes a polarization conversion/electrooptic tuning section 12 which includes an integral

1 number N_c of relatively short polarization coupling regions 14 of length L_1. Polarization

2 coupling regions 14 are separated by considerably longer, non-polarization regions , regions 16

3 of length L_2 where no polarization coupling occurs, as illustrated in Fig. 6. Total length L_{tot} of

4 the polarization conversion/electrooptic tuning region 12 is given by

5 $$L_{tot} = N_c L_1 + (N_c-1)L_2 \qquad (2)$$

6 It is important to note that spatial coherence of the more than one set of spaced apart, spatially

7 periodic, strain-inducing pads 18 must be maintained over the entire length of the polarization

8 conversion/electrooptic tuning region 12. Thus, the center-to-center spacing between any two of

9 the pads 18 is exactly an integer times Λ, even if the two pads 18 are from different groups.

10 Another important feature of the filter 10 of the present invention is to apodize the

11 strength of coupling induced by the strain pads 18 i.e., to make the coupling strength a function

12 of position over the length of the polarization conversion/electrooptic tuning region 12. This can

13 be accomplished by varying the width of the pads 18 (as illustrated in Figure 15)- narrower pads

14 will produce weaker polarization coupling. Calculations show that apodization in which the

15 coupling is strongest at the center 20 of the polarization conversion/electrooptic tuning section 12

16 and tapers monotonically toward the edges 22 provides the spectral characteristics needed for

17 equally spaced channels in a WDM system.

18 Predicted spectral response for the case of a lithium niobate substrate with $N_c = 12$, $L_1 =$

19 .03 cm, and $L_2 = .31$ cm is plotted in Figs. 7 and 8. The coupling constant values were apodized

20 according to the formula

21 $$\kappa = \kappa_0 + \kappa_1 \cos[2\pi(z-L_{tot}/2)], \qquad (3)$$

1   with $\kappa_0 = 1.39$ cm^{-1} and $\kappa_1 = .35$ cm^{-1}, and z the position relative to the start of the polarization

2   coupling region. In this case L_{tot} is calculated from eq. (2) to be 3.77 cm.

3   Fig. 7. illustrates the predicted polarization conversion efficiency vs. optical frequency

4   for waveguide section of Fig. 6 with apodized coupling, plotted using the following parameters:

5    $N_c = 12$, $L_1 = .03$ cm, $L_2 = .31$ cm, $\kappa = 1.39$ cm^{-1}, $\kappa_0 = 0.35$ cm^{-1}.

6   The spectral characteristic of Fig. 7, which corresponds to alternating coupling 14/non-

7   coupling 16 regions as in Fig. 6, is almost a periodic function of frequency. This contrasts with

8   the Prior Art spectrum of Fig. 4, which corresponds to uniform coupling as in Prior Art Fig. 3, in

9   which there is only one main peak. A second difference is that the nulls are almost equally

10   spaced at 100 GHz intervals in the plot of the present invention 10 shown in Fig. 7, whereas the

11   spacing between nulls varies considerably in the plot of Prior Art Fig. 4. This is best seen by

12   comparing the plots in Figs. 5 (Prior Art) and 8 (present invention), which have expanded

13   horizontal (frequency) axes.

14   For the filter 10 design of the present invention as illustrated in Fig. 6, the spacing

15   between adjacent principal peaks corresponds to the frequency change Δv which produces a 2π

16   radian value for the phase change $\Delta\phi$ between the TE and TM polarization components for light

17   propagating over one spatial period of length $L_1 + L_2$. Since

18                 $$\Delta\phi = 2\pi(n_1 - n_3)\Delta v(L_1+L_2)/c, \qquad (4)$$

19   it follows that

20                 $$\Delta v = c/[(n_1-n_3)(L_1+L_2)]. \qquad (5)$$

21   In the plots of Figs. 7 and 8, the spacing between principal peaks is $\Delta v = 1200$ GHZ, or

22   N_c times the spacing between one of the peaks and an adjacent null.

12

1   By way of a further advantage of the present invention, by configuring filters 10 with

2   different values of N_c in series, it is possible to greatly increase the number of channels which

3   can be accessed using moderate tuning voltages. One configuration for accomplishing this with

4   three EOTF's in series is illustrated in Fig. 9. The first filter 10 selects N_{c2} frequency channels

5   spaced N_{c1} channels apart. The second EOTF filter 10 with a spacing between principal peaks of

6   N_{c2} channels selects one of the N_{c2} frequency channels as the output (drop) frequency. The third

7   EOTF filter 10 with a spacing between principal peaks of N_{c1} channels combines N_{c2}-1 of the N_{c2}

8   frequencies selected by the first EOTF with all of the frequencies not selected by the first EOTF.

9   Fig. 10. is an illustration of frequency selection by EOTF's in series, with N_{c1} = 4 and N_{c2}

10   = 3. The frequency channels 22 selected by each filter 10 are indicated by vertical lines on the

11   diagrams. A frequency channel 22 is removed when two of the vertical lines correspond to the

12   same frequency channel. A tuning voltage applied to each filter 10 causes a translation in

13   frequency of its polarization-converted spectrum, but does not affect the frequency spacing

14   between principal peaks. By independently varying the two tuning voltages, any of the 12

15   frequencies can be selected, as indicated by an arrow in the diagram.

16   The number of independently accessible frequency channels 22 is N_{c1} x N_{c2}, provided that

17   1 is the only common factor of these two integers. Tuning of the spectral characteristics of filters

18   10 with N_{c1} = 4 and N_{c2} = 3 in series to select particular frequency channels is illustrated in Fig.

19   10.

20   The use of two filters 10 in series greatly increases the number of frequency channels

21   which can be accessed, subject to a constraint on the maximum voltage which can be applied to

22   an EOTF. The voltage required to tune over the entire frequency range of one of the EOTF's is

13

1   that needed to produce a $\pm\pi$ radian change in $\Delta\phi$, the phase difference between the TE and TM

2   polarization components for light propagating over one spatial period of length $L_1 + L_2$. This

3   voltage-induced phase change is

4
$$\Delta\phi = 2\pi v^*(L_1+L_2)\Delta(n_1-n_3)/c, \qquad\qquad (4)$$

5   with v^* the center frequency in the optical spectrum and $\Delta(n_1-n_3)$ the voltage-induced

6   birefringence change. Using parameters appropriate to lithium niobate at a wavelength of 1545

7   nm, with $L_1 + L_2 = .34$ cm, it is estimated that a voltage change of ±42 V will be required to

8   access 12 wavelengths in a single-stage EOTF with $N_c = 12$. Using the configuration of Fig. 9

9   with $N_{c1} = 12$ and $N_{c2} = 11$, it is possible to access 132 WDM channels without increasing the

10   required voltage. To access this many channels with a single Prior Art EOTF would require a

11   voltage swing about 11 times larger, or ±462 V. Such large voltages would undoubtedly degrade

12   or destroy the device.

13   A reflective arrangement for achieving closer WDM channel spacings for a substrate of a

14   given length is shown in Fig. 11. The benefit of this arrangement is that the effective length for

15   polarization conversion and electrooptic tuning is twice the physical length, and only one beam

16   splitter 24 is needed. This makes it possible to construct an EOTF with 50 GHz channel spacing

17   on a 3" wafer. The reflective embodiment of the present invention includes a single waveguide

18   26 in substrate 28, and an electrode 30. In addition to the strain-inducing pads 18 this

19   embodiment includes a reflector 32. As a result, this embodiment of filter 10 has only two

20   physical ports, but it can be operated as a four-port device as required for most WDM

21   applications through the use of two optical circulators 34 connected by optical fiber 36, as shown

22   in Fig. 12. Also shown in Fig.11 is ground 38 and voltage tuner 40. Voltage tuner 40 is any

1   voltage application device now known or hereafter developed for applying varying amounts of

2   voltage.

3   Fig. 11. illustrates a reflective configuration for EOTF 10. The reflecting surface could

4   be a multilayer dielectric film or a metal film deposited on the end of the substrate.

5   For the embodiment of the invention 10 of Figs. 11 and 12, if the total length of the

6   polarization conversion/electrooptic interaction region 12 is 3.77 cm, with twelve separate

7   polarization conversion regions 12, then the filter 10 would have the spectral characteristics of a

8   non-reflective device with a channel spacing of 50 GHz and a spacing between principal

9   conversion peaks of 1200 GHz, or 24 channels.

10   As another important feature of the present invention, the applicants have determined that

11 the difference in time delay for the two polarizations of light in the EOTF's can be compensated

12 by using a polarization maintaining (PM) fiber 42 of sufficient length following each EOTF 10.

13 The PM fiber 42 is oriented such that light polarized along the slow axis of the EOTF 10 is

14 polarized along the fast axis of the PM fiber 42, and vice versa. For example, if the fiber 42 has

15 a 0.1% birefringence and a group refractive index of 1.46, the differential delay is

16 $0.001 \times 1.46 / 2.998 \times 10^8$ seconds per meter length of fiber 42, or 4.9 ps per meter. Thus the 17 ps

17 of differential delay between the polarization states in the example introduced earlier would be

18 canceled by 3.5 m of PM fiber 42. This technique is applicable for a single EOTF, as in Figs. 6,

19 13 and 16 for example, for EOTF's in a series arrangement, as in Fig. 9, or for the reflective

20 configuration of Figs. 11 and 12.

21   Referring now to Figs. 13 and 14, the full version of the filter 10 of the present invention

22 is set forth as partially illustrated in Figs. 6. The filter 10 includes two input single mode

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1   waveguides 44 followed by a first beam splitter 24. A polarization converter 46 is connected

2   thereafter. The polarization converter 46 is composed of more than one set of spaced apart,

3   spatially periodic, strain-inducing pads 18, as previously discussed. Electrodes 30 are located on

4   substrate 28 connected in proximity to the polarization converter 46. Thereafter, a second beam

5   splitter 24 is connected to output waveguides 48. Fig. 14 illustrates strain pads 18 slanted which

6   eliminates the need for polarizing beam splitters.

7   Fig. 15 illustrates the embodiment of the invention whereby the polarization coupling

8   strength is apodized by varying the width of the strain-inducing pads 18. As illustrated, the

9   polarization coupling is strongest at the center 20 of the polarization conversion region 12 were

10 the strain-inducing pads 18 are wider.

11   Figs. 16 and 17 illustrate the use of polarization maintaining fiber 42, as previously

12 discussed above.

13   The tunable filter 10, fabricated on an electrooptic substrate material 28, consists of two

14 input single mode waveguides 44 followed by a beam splitter 24. Light leaving the beam splitter

15 24 is divided between two parallel waveguide sections 50 and 52 , each of which contains a

16 polarization converter 46. Each of these polarization converters 46 features a set of spatially

17 periodic, strain-inducing, thin-film dielectric strips/pads 18 which cross over the waveguide

18 sections 50 and 52 for inducing coupling between orthogonally polarized modes of light, and

19 electrode(s) 30 for applying an electric field across the waveguide. The waveguides 50 and 52

20 containing the polarization converter 46 converge in a second beam splitter 24, then separate to

21 form the two output waveguides 48.

1   The add-drop filter 10 adds a narrow range of optical frequencies to an optical fiber 36

2   which may contain other optical frequencies, and drops (removes) a narrow range of optical

3   frequencies from a fiber 36 while leaving other frequencies unaffected.

4   In summary, the invention described herein relates to a new tunable filter 10 which

5   provides a combination of narrow interchannel frequency spacing (50 GHZ or 100 GHZ), low-

6   voltage operation, and extremely wide frequency tuning range.

7   Add-drop filters are key components for wavelength-division-multiplexed fiber optic

8   communication systems. No other technology offers the combination of tuning speed (<< 1 μs)

9   and tuning range (>>30 nm) of the filter 10 disclosed herein.

10   The description of the present embodiments of the invention have been presented for

11   purposes of illustration, but are not intended to be exhaustive or to limit the invention to the form

12   disclosed. Many modifications and variations will be apparent to those of ordinary skill in the

13   art. As such, while the present invention has been disclosed in connection with the preferred

14   embodiment thereof, it should be understood that there may be other embodiments which fall

15   within the spirit and scope of the invention as defined by the following claims.

16